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PROPULSION DIRECTORATE/CONTROL AND ENGINE HEALTH MANAGEMENT (CEHM): REAL-TIME TURBOFAN ENGINE SIMULATION

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14. ABSTRACT
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14. ABSTRACT (concluded)

Key parameters of comparison are the three states of the engine, low pressure spool speed (XNL), high pressure spool speed (XNH), and core metal temperature (TMPC), and burner fuel flow (WF36) and net thrust (FN). It is observed with each parameter that the average percent error is less than 1%. Thus, a successful real-time implementation is achieved while maintaining a high degree of accuracy. The model's behavior now approximates a real gas turbine and provides an ideal test bed for observing faults and failures, engine parameter variations, and degradation over time. This in turn provides a valuable tool in observing the symptoms of failure, developing diagnostics routines, and improving prognostic algorithms.

Propulsion Directorate/Control and Engine Health Management (CEHM): Real-Time Turbofan Engine Simulation[1, 2]

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Abstract—As the interest in intelligent engine technology increases so does the demand for advanced methods of engine model simulation. Undoubtedly, this element is very cost effective, in that, it can decrease test and experimentation hours significantly. In order to extract more meaningful information for analysis, model simulation must be conducted in a real-time environment. The Modular Aero-Propulsion System Simulation (MAPSS) is a generic turbofan engine simulation derived from FORTRAN-based coding developed at NASA Glenn Research Center. It is a non-real time, multi-rate system composed of the Controller and Actuator Dynamics (CAD) and Component Level Model (CLM) modules, representing the digital controller and engine, respectively. This paper discusses the implementation and simulation of the MAPSS model in a real-time environment. The controller and engine are loaded on two separate simulators with data transfer between the two systems via a set of electrical cables. This analysis platform encompasses all of the aspects of a real-time environment with plant and sensor noise. The real-time implementation is validated against the non-real time simulation through transient and steady-state conditions. Key parameters of comparison are the three states of the engine, low pressure spool speed (XNL), high pressure spool speed (XNH), and core metal temperature (TMPC), and burner fuel flow (WF36) and net thrust (FN). It is observed with each parameter that the average percent error is less than 1%. Thus, a successful real-time implementation is achieved while maintaining a high degree of accuracy. The model's behavior now approximates a real gas turbine and provides an ideal test bed for observing faults and failures, engine parameter variations, and degradation over time. This in turn provides a valuable tool in observing the symptoms of failure, developing diagnostics routines, and improving prognostic algorithms.

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1. INTRODUCTION

Perhaps one of the most useful design tools in control and engine health management is model simulation. Arguably, this is the most critical area in the process of design and analysis. As the interest in intelligent engine technology increases so does the demand for advanced methods of engine model simulation. Specifically, real-time model simulation that allows interface with physical hardware, such as sensors, actuators and valves, are very practical. Undoubtedly, this element is very cost effective, in that, it can decrease test and experimentation hours significantly and these test procedures can be conducted without any fuel consumption. In turn, overall cost can be reduced by millions. The key factor is to initiate this process with a high-quality model of the engine, itself. As with any system, the quality of the data obtained from simulation is only as good as the model in simulation. Obviously, the characteristics of an engine and its control can be very meticulous and complex, as it pertains to modeling. Therefore, a large amount of time and effort is spent in the developmental stages of a detailed engine model. However,

[1] 0-7803-8155-6/04/$17.00© 2004 IEEE
[2] IEEEAC paper #1291, Version 2, Updated January 8, 2004

in order to extract meaningful information for analysis, or allow external hardware to be tested, simulation of the model must be conducted in a real-time environment. These tools produce more realistic data and allow a more accurate platform for control systems design.

Modular Aero-Propulsion System Simulation

The Modular Aero-Propulsion System Simulation (MAPSS) is a generic turbofan engine simulation derived from FORTRAN-based coding developed at NASA Glenn Research Center. It is constructed in Simulink®, a computer aided control design and simulation package that allows graphical representation of dynamical systems in a block diagram form. The aim is to demonstrate a flexible turbofan engine simulation platform that will allow easy access to health, engine, and control parameters, as well as a quick way to test control and diagnostic systems [1].

MAPSS is a non-real time, multi-rate system composed of the Controller and Actuator Dynamics (CAD) and Component Level Model (CLM) modules. The controller in the CAD module emulates the functionality of a digital controller, which has a typical sampling rate of 50 Hz. The CLM module simulates the dynamics of the engine and uses a much faster updating rate. The actuators in the CAD module use the same update rate as the CLM. Due to the time constants used by the actuators, this rate is 2500 Hz [1].

The engine that is being implemented, shown in Figure 1, is a low frequency, transient, performance model of a high-pressure ratio, dual-spool, low-bypass, military-type turbofan engine with a digital controller. The components of this engine model are a single stage high-pressure ratio fan with variable inlet stator vanes, booster with independent hub and tip stator vanes, high-pressure mixed flow compressor, double-annular combustor, high- and low-pressure turbines, afterburner, and nozzle components. Also included are forward blocker doors and an aft variable area bypass injector (VABI), giving the engine variable cycle capability [1].

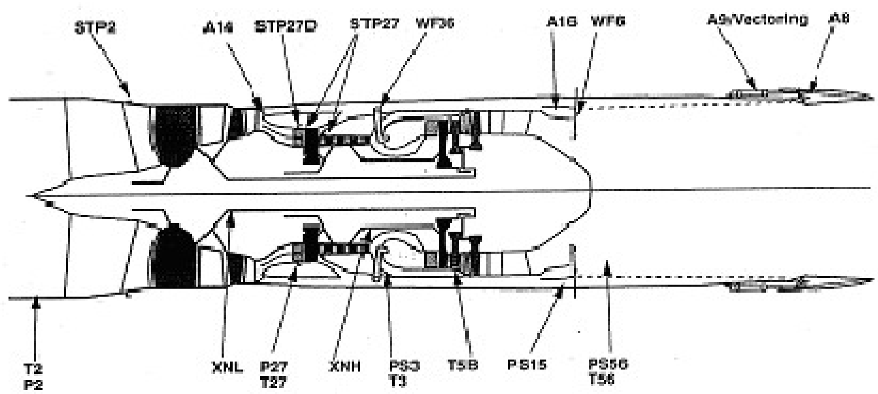

Figure 1 – Schematic of turbofan engine model with labeled sensors and actuators.

The engine model, represented as a CLM, links individual component models of state space and non-linear algebraic equations, along with their accompanying maps modeling the component characteristics. The CLM uses fan and core rotor speeds, as well as average hot section temperature (i.e. metal temperature) as state variables or variables of control. The actuators listed are for the fan variable inlet stator vanes (STP2), forward blocker door area positioning (A14), booster tip stator vanes (STP27D), high-pressure compressor and booster hub stator vanes (STP27), burner fuel flow (WF36), VABI area positioning (A16), afterburner fuel flow (WF6), and nozzle throat and exit area positioning (A8 and A9, respectively). The sensors used by the controller measure fan inlet temperature (T2) and pressure (P2), fan rotor speed (XNL), high-pressure compressor inlet temperature (T27) and pressure (P27), core rotor speed (XNH), high-pressure compressor exit temperature (T3) and static pressure (PS3), low-pressure turbine blade temperature (T5B), bypass duct static pressure at the mixing plane (PS15), low-pressure turbine exit temperature (T56) and static pressure (PS56) [1].

The digital controller, having power lever angle (PLA), Mach number, and altitude as inputs, runs at a fixed time frame for sampling sensor inputs and issuing actuator commands. It uses an open loop scheduler to control the stator vane actuators. Proportional-plus-integral (PI) control is used to regulate WF36, A8, and A16 through high, medium, and low PLA power settings. The PLA is also used in control logic to position A14 [1].

It can be seen that MAPSS possesses the complexity and details of a real jet engine; however, it should be noted that it is limited by its non-real time simulation. It would be more beneficial to obtain performance criteria from this system within a more realistic framework. Thus, to extend the capabilities of MAPSS, increasing the effectiveness of analysis, the implementation of this model into a real-time simulation environment is necessary.

Intelligent Control Facility

The Intelligent Control Facility (ICF) was established to provide a real-time simulation and analysis platform for investigation of modern turbine engine and control system behavior. The ICF uses state-of-the-art simulation hardware and software, supplied by dSPACE, Inc., a leader in the field of real-time simulation of large scale power and control systems [2]. The dSPACE Controller Development and Testing System consists of a high end Rapid Control Prototyping (RCP) and a Hardware-In-The-Loop (HIL) system. These separate simulation systems are used to provide the high fidelity virtual operating environment. The HIL system simulates the plant, i.e. the engine model, complete with all related sensors and actuators. The RCP system simulates the engine controller, complete with all logic, switching, inputs and outputs. The RCP behaves like a FADEC while connected to an aircraft engine with the flexibility to monitor, modify and acquire various parameters of the control system. Data transfer between the two systems is via a set of electrical cables, which carry the actual physical signals that exist in an operating aircraft engine. This architecture results in a tool that can be used to not only simulate an engine controller, but to interconnect the real and virtual components of the propulsion system at will. The versatility of these simulators also allows operational testing of individual engine and control components such as sensors, actuators and valves [2].

Operation of the real-time simulation is achieved using the ControlDesk graphical interface software. ControlDesk is the central module of the dSPACE experiment software that affords users a convenient way of managing and instrumenting experiments. Using the integrated Simulink® interface, controller models can be tested offline. The same virtual instruments, parameter sets and automated test loops can be used to transition from Simulink® to dSPACE real-time and back. With this software a visual representation of an aircraft cockpit to be duplicated, complete with dials, knobs and gage readings. A snapshot of the RCP and HIL layouts for the MAPSS real-time simulation is shown in Figure 2(a) and (b), respectively.

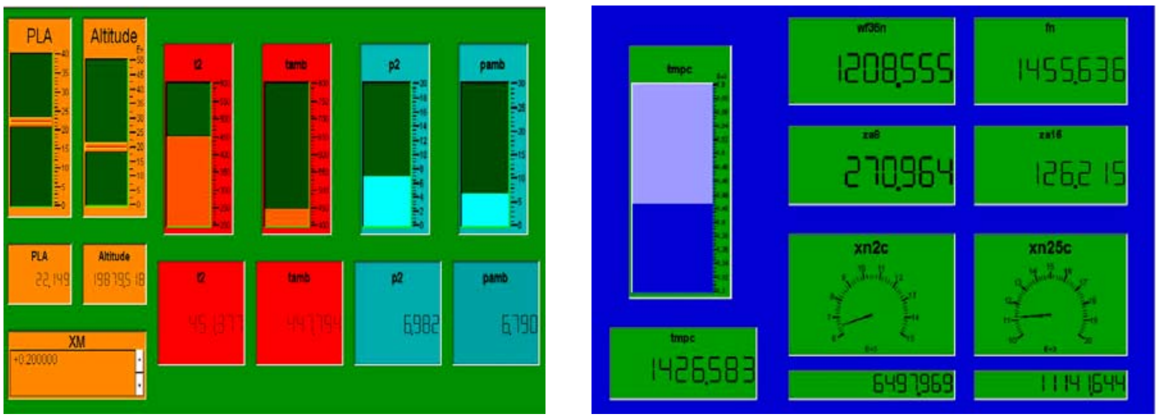

Figure 2 – ControlDesk layout of MAPSS real-time simulation

Given the capacity and capabilities of the ICF, it provides an appropriate facility for the implementation of MAPSS in real-time simulation. With the available resources performance can be analyzed in an environment that encompasses all of the realistic elements, down to real sensor noise between interfaces. It is the aim of the CEHM team, through the use of the ICF, to utilize the real-time simulation of MAPSS to produce a more powerful tool for controller design, performance and analysis.

2. REAL-TIME IMPLEMENTATION

The initial step in preparing a compatible structure for the dSPACE simulation environment is to obtain two independent controller and plant (engine) models. Therefore, the MAPSS Simulink® model is first separated into its individual core components. After assigning the outputs of each to the appropriate channels, the two models are compiled and loaded onto the dSPACE processor boards. Data transfers and interrupts between systems are executed through high-speed optical interface. The controller output signals, i.e. the actuator positions, are transmitted as inputs to the engine through the use of dSPACE real-time interface (RTI) hardware. Similarly, the sensor feedback signals are transmitted from the engine to the controller via thermocouples, pressure and speed sensors within the architecture of the RTI. The independent systems both demonstrated high processing rates comparable to the sampling rates used by MAPSS. One pass through the RCP and HIL systems had an average turnaround time of 160 and 764 μsec, respectively.

As with any real dynamic system, signal corruption due to bias or sensor noise becomes an apparent issue. Compensation for sensor bias in the hardware is achieved by adding an offset of the respective parameter value within the Simulink® model. Of course, sensor noise, with certain measures, can be reduced but not completely eliminated. Parallel to real-life systems, a small degree of sensor noise is acceptable with minimal effects to the integrity of the overall system performance. Therefore, with minor adjustments to speed sensor noise filters and calibrations, the system is simulated under normal operating conditions.

Simulation Conditions

In order to assess the accuracy of MAPSS implemented in real-time as compared the non-real time simulation equivalent operating conditions are set for each. For a complete evaluation both transient and steady state performance are considered. As a result of a predefined operating condition the MAPSS Simulink® model has to be initialized from ground idle settings which are the minimum PLA of 21 and Mach number and altitude of zero (0). After initialization these inputs can be modified to represent a given flight envelope. To produce transient simulation conditions, the Mach number and altitude both remain at constant zero (0) values. Simulations are performed with two dynamic ranges of PLA settings. The first is a very large step from the minimum setting of 21 to maximum power PLA setting of 50. A much smaller step is taken from minimum setting to the next degree increment of 22. As a point of reference the parameters used for comparison are the three states of the engine, low pressure spool speed (XNL), high pressure spool speed (XNH), and core metal temperature (TMPC), and also burner fuel flow (WF36) and net thrust (FN).

The simulations are run for a window of 40 seconds with the PLA step occurring at about 7 seconds at a rate of 5 degrees per second. This window allows sufficient time for the system to transition through the flight envelope. The transient performance is then observed followed by the ensuing steady-state behavior. The plots of the parameter comparisons are shown where the blue and pink lines represent the non-real time and real-time simulations, respectively.

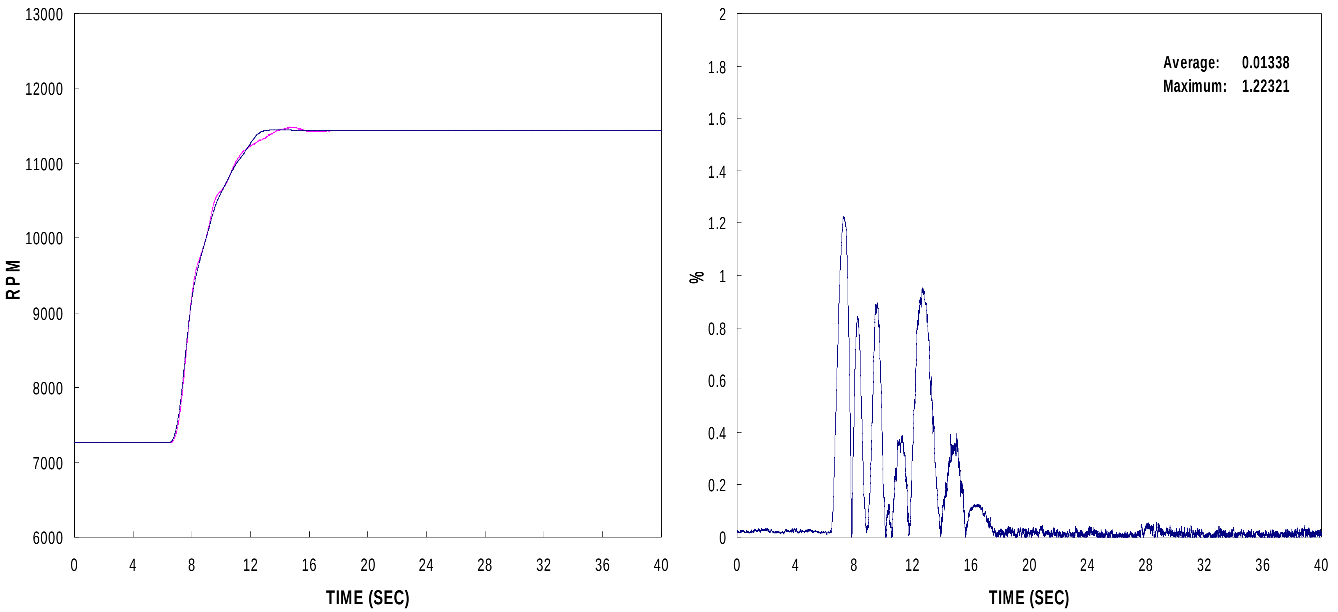

Figure 3 – Low pressure spool speed (XNL) parameter performance

3. Simulation Results

The given results show the actual performance of the chosen parameters along with the percent error. Figures 3-7 show the behavior with the PLA step from 21 to 50, while the smaller step (PLA from 21 to 22) behaviors are represented in Figures 8-12 (Appendix).

In the case of the large PLA step it can be seen from the figures that the dSPACE simulation corresponds very well with the Simulink® simulation. With each parameter the average percent error (APE) is below 0.05% and the maximum percent error (MPE) is below a value of 4%, with the exception of the fuel flow (Figure 7). In the case of the fuel flow the APE is just below 0.5% while the MPE is above 5% percent, but is still significantly small. This shows the accuracy of the dSPACE real-time simulation, notwithstanding the presence of sensor noise, which is apparent in the parameter readings.

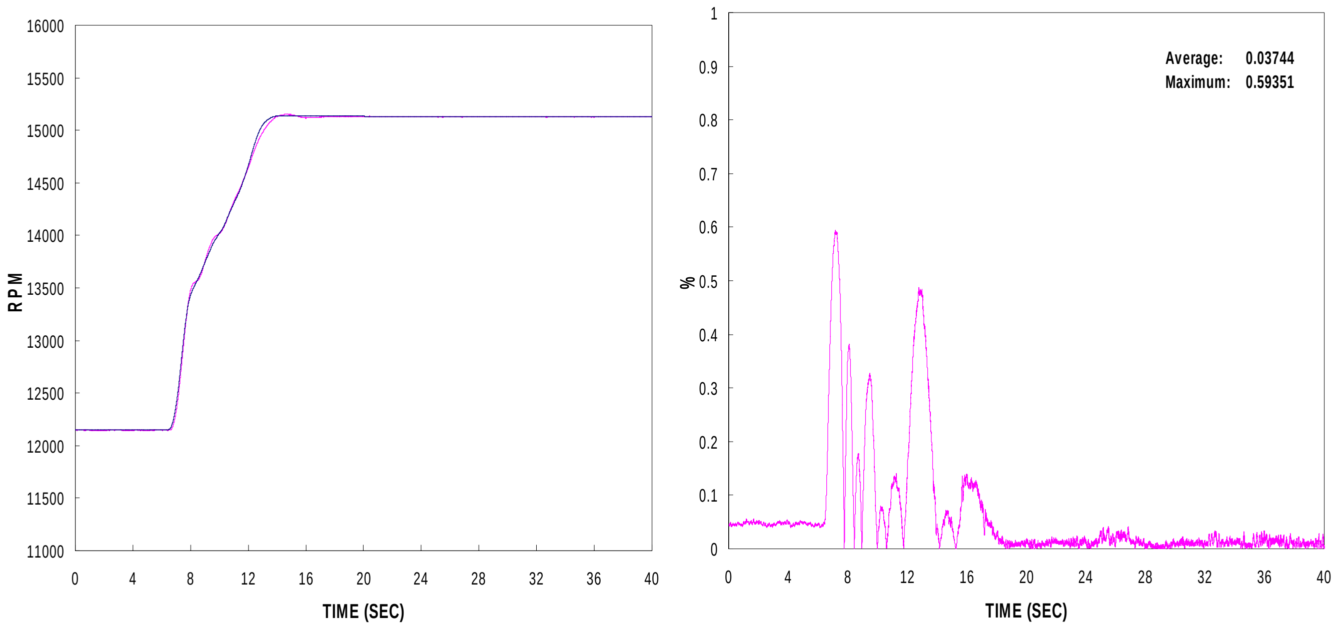

Figure 4 – High pressure spool speed (XNH) parameter performance.

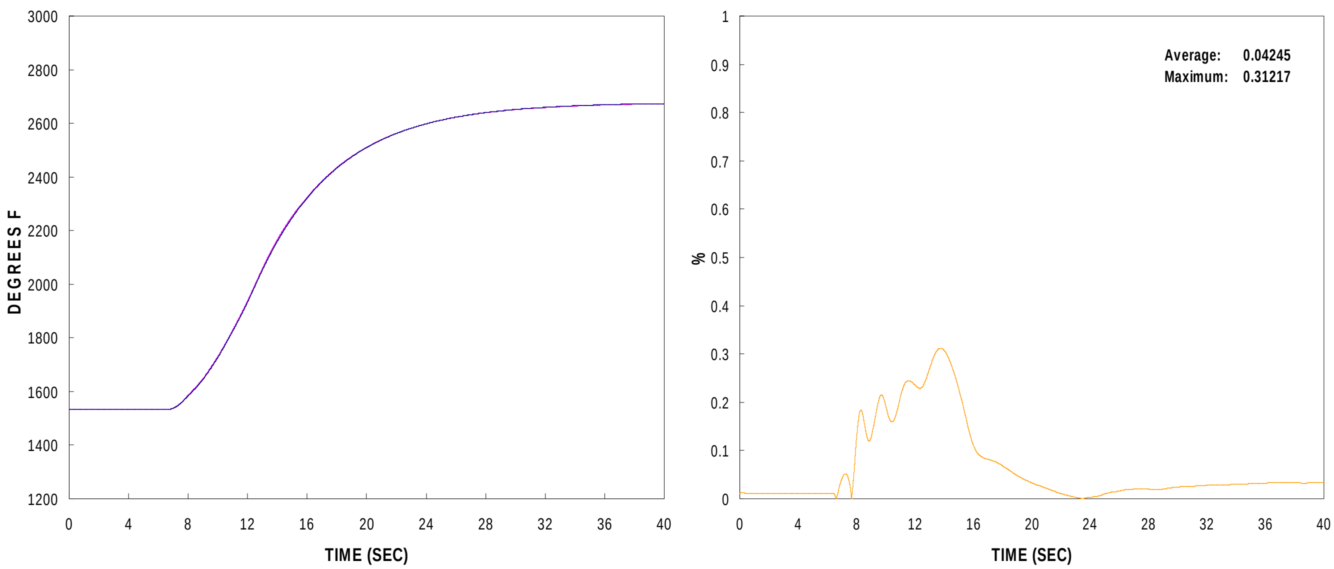

Figure 5 – Core metal temperature (TMPC) parameter performance.

It is observed that in the transient portion of the simulation the dSPACE performance closely follows that of the Simulink®, while steady-state trends exhibit much higher accuracy with all steady-state measuring less than 0.1%. The largest amounts of steady-state error are seen in the net thrust and fuel flow parameters which are just under 0.1%, whereas the three state parameters each have an error less than 0.06%.

Similar parameter behavior and trends are observed with the smaller PLA step; however, errors between the non-real time and real-time simulations are slightly smaller in both transient and steady-state phases of the flight envelope. Given this step the APE for each parameter is less then 0.05% and the MPE is less than 1%, with the exception of the fuel flow parameter. Though this parameter exhibited the largest error the APE is considerably small at only 0.241% and the MPE at 1.282%. The simulation again shows sound steady-state properties with each parameter, excluding fuel flow, measuring less than 0.05% error. Again, though the fuel flow parameter is higher it only measured a steady-state error of approximately 0.175%.

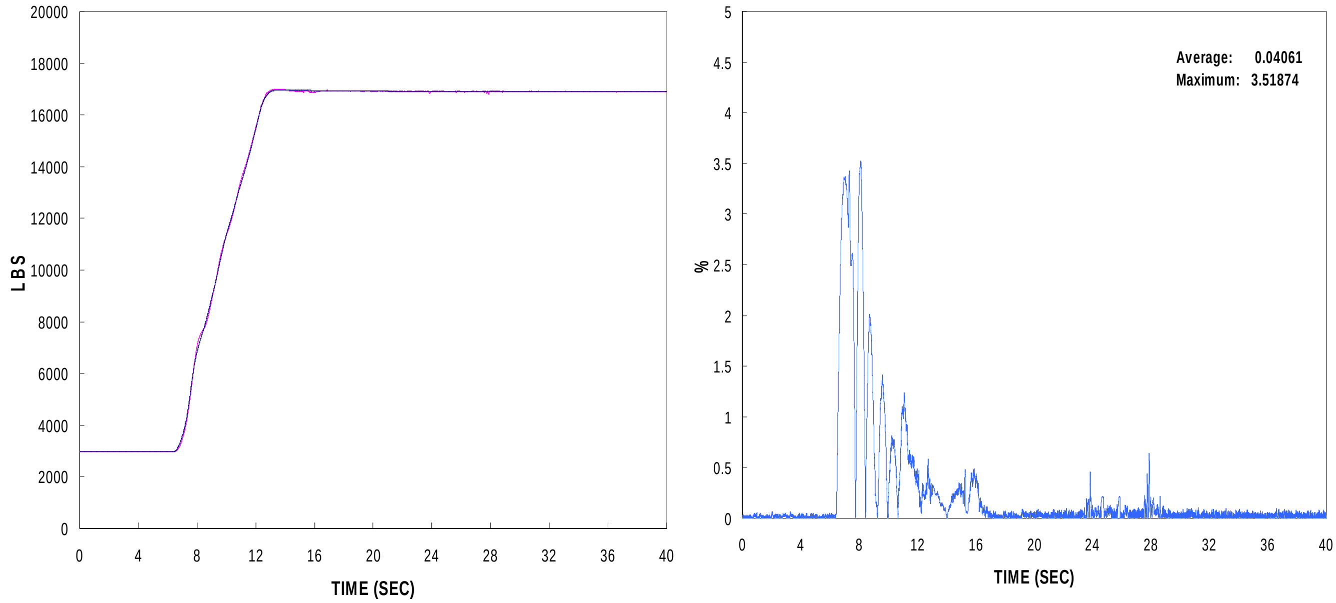

Figure 6 – Net thrust (FN) parameter performance.

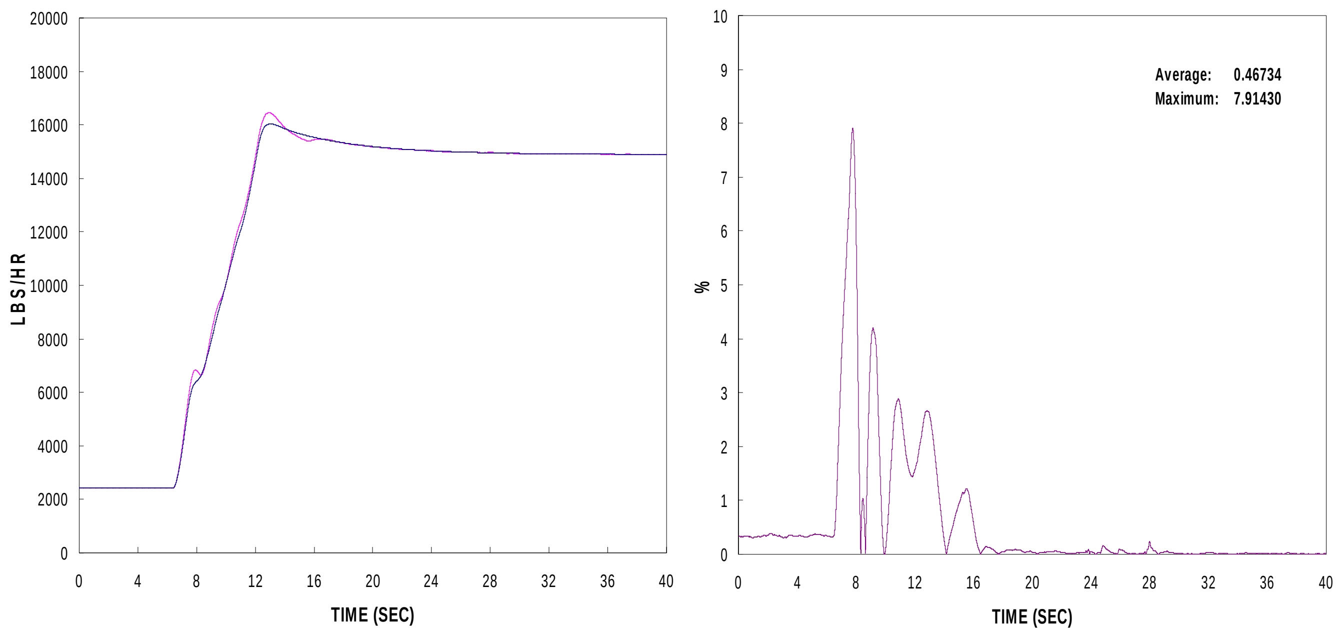

Figure 7 – Burner fuel flow (WF36) parameter performance.

4. Conclusions

In order to more realistically simulate a turbofan engine model and extract useful data for analysis the Modular Aero-Propulsion System Simulation (MAPSS) model is implemented in a real-time environment. By separating the controller and engine modules into two independently operating systems, actual signal transfer between the two is realized. A validation of the implementation is performed by comparing key parameters of the model in both real-time and non-real time simulations. With each parameter comparison the average percent error is less than 1% and in many cases it is less than ½%. This system integrity is maintained throughout each flight envelope even in the presence of plant and sensor noise. Thus, a successful real-time implementation is achieved while maintaining a high degree of accuracy. The model's behavior now approximates a real gas turbine and provides an ideal test bed for observing faults and failures, engine parameter variations, and degradation over time. This in turn provides a valuable tool in observing the symptoms of failure, developing diagnostics routines, and improving prognostic algorithms.

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REFERENCES

[1] Parker, K. I., Guo, T. H., "Development of a Turbofan Engine Simulation in a Graphical Simulation Environment," NASA/TM--2003-212843.

[2] Air Force Research Laboratory / Propulsion Directorate: Intelligent Control Facility. http://www.pr.afrl.af.mil/facilities/pr_east/icf.htm

BIOGRAPHIES

Tramone Curry is a native of Atlanta, GA. He is a Ph.D. candidate in mechanical engineering at Florida A&M University – FAMU/FSU College of Engineering. He received his BSME and MSME from Florida A&M University and has over 5 years of research experience in controls engineering.

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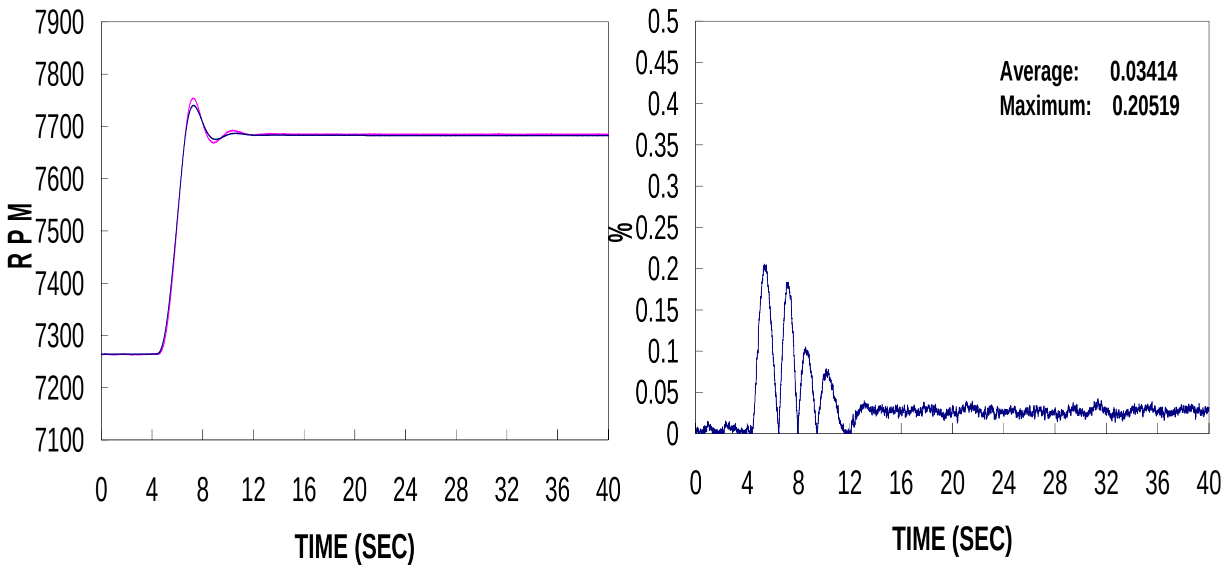
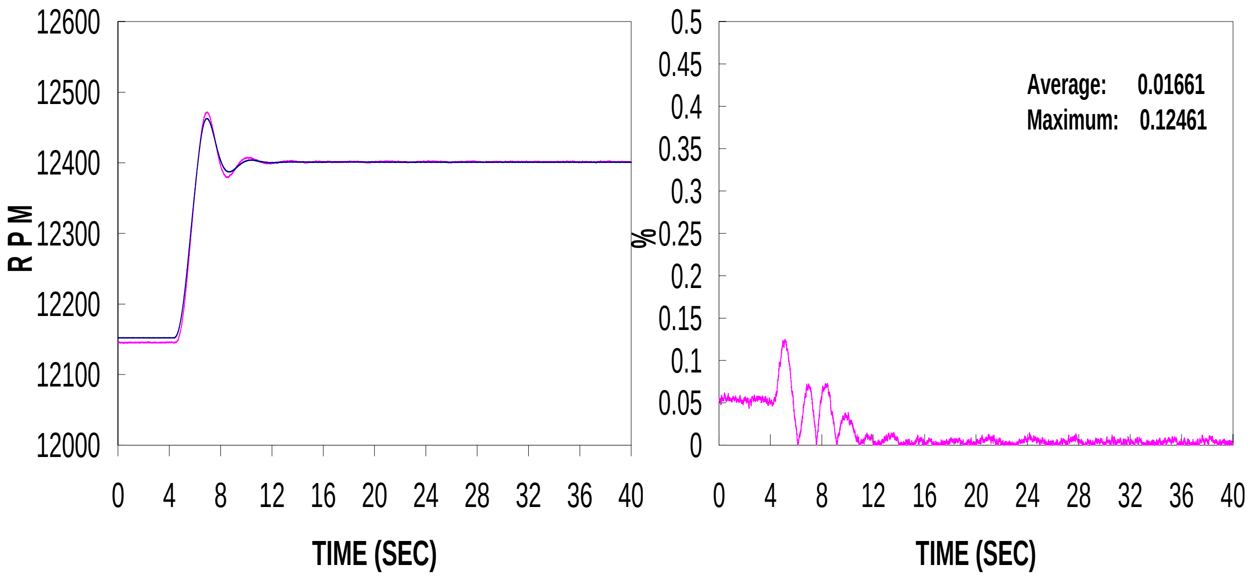
APPENDIX

PLA STEP 21-22



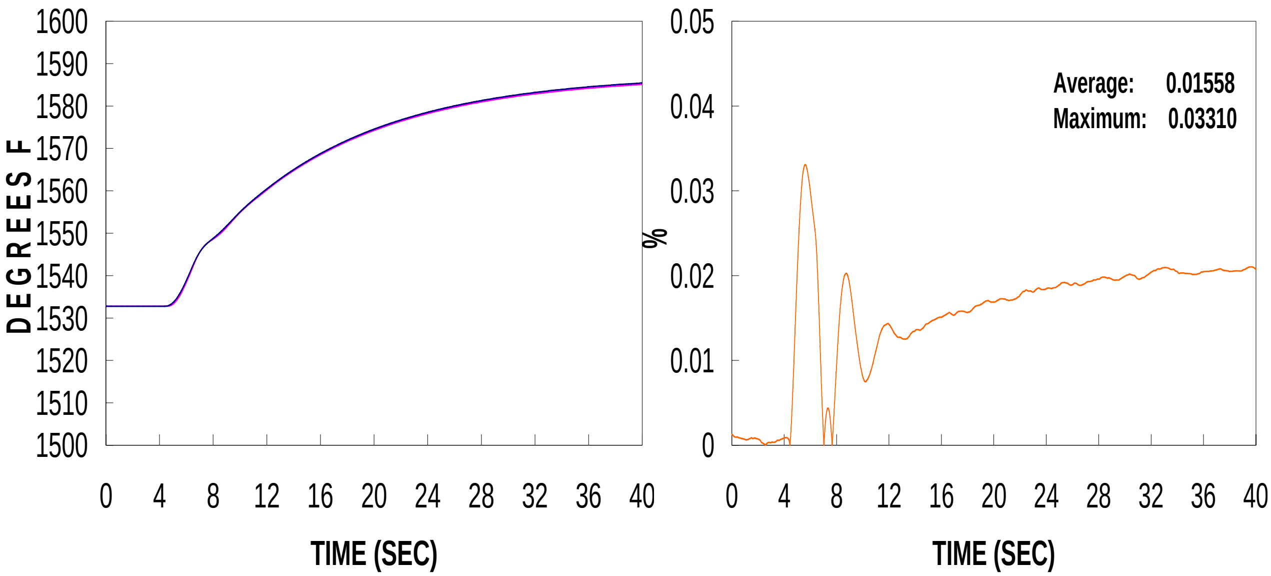
(a) **(b)**

Figure 8 - Low pressure spool speed (XNL) parameter performance (a) and percent error (b).



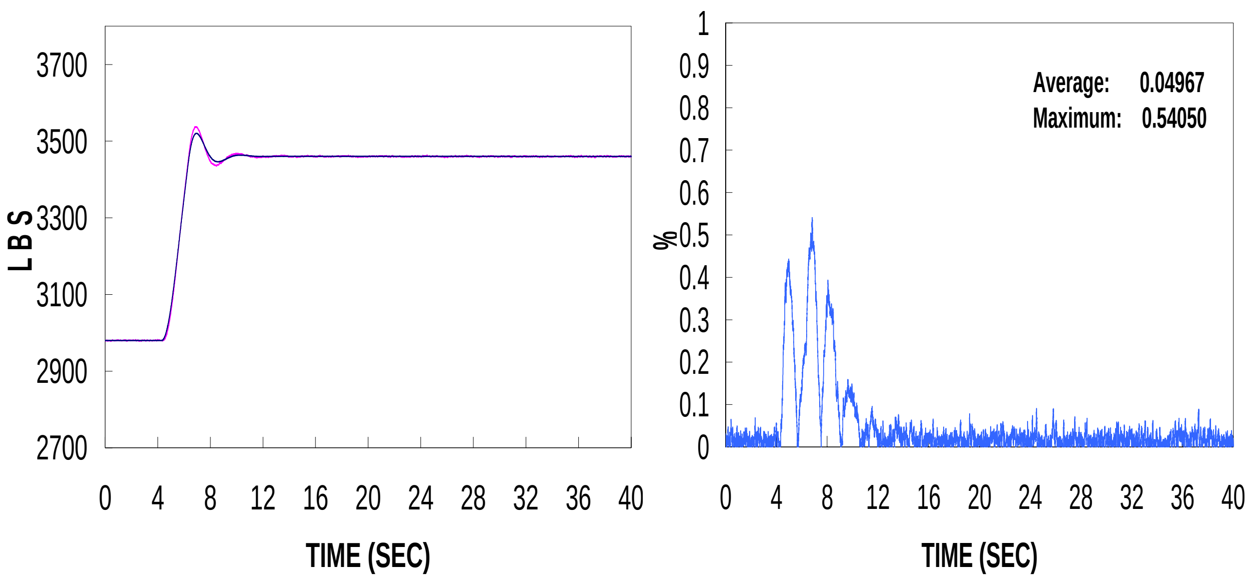
(a) **(b)**

Figure 9 - High pressure spool speed (XNH) parameter performance (a) and percent error (b).



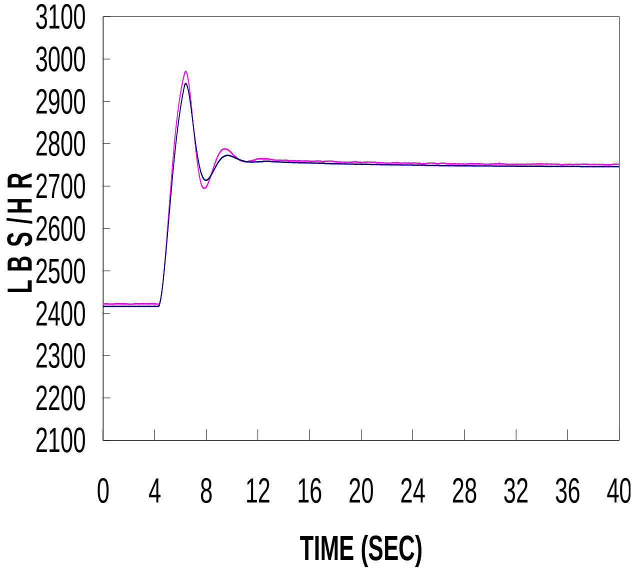
(a) **(b)**

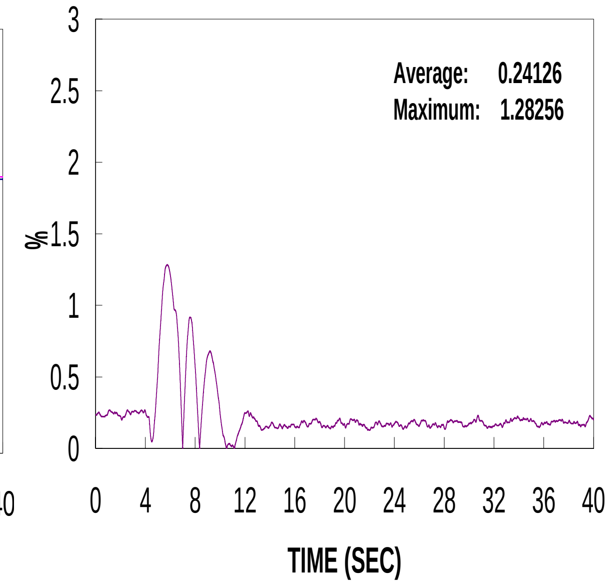
Figure 10 - Core Metal Temperature (TMPC) parameter performance (a) and percent error (b).



(a) **(b)**

Figure 11 - Net Thrust (FN) parameter performance (a) and percent error (b).





(a) **(b)**

Figure 12 - Burner Fuel Flow (WF36) parameter performance (a) and percent error (b).